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Making Use of Optimization, NonDeterministic Analysis, and Numerical Simulation to Assess Firing Set Robustness in a Fire[1]

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Abstract

One emphasis of weapon surety (safety and security) at Sandia National Laboratories is the assessment of fire-related risk to weapon systems. New developments in computing hardware and software make possible the application of a new generation of very powerful analysis tools for surety assessment. This paper illustrates the application of some of these computational tools to assess the robustness of a conceptual firing set design in severe thermal environments. With these assessment tools, systematic interrogation of the parameter space governing the thermal robustness of the firing set has revealed much greater vulnerability than traditional ad hoc techniques had indicated. These newer techniques should be routinely applied in weapon design and assessment to produce more fully characterized and robust systems where weapon surety is paramount. As well as helping expose and quantify vulnerabilities in systems, these tools can be used in design and resource allocation processes to build safer, more reliable, more optimal systems.

Introduction

Thermally induced failures and indeterminacies in high-consequence structures and systems such as aircraft, weapon systems, naval vessels, petrochemical processing plants, etc. put people and engineered systems at risk. It is highly desirable to design such systems to that the risk of fire-triggered catastrophes is mitigated. This requires probing the thermal robustness of candidate designs in various credible thermal environments.

In today's computing environment, experimentally validated computer models of the behavior of such systems can be combined with optimization and sensitivity/uncertainty assessment procedures to address, in a systematic manner, bigger questions than previously possible: What is the optimal solution? What is the level of risk involved? What are the sensitivities and uncertainties and their implications? What are the economics of the trade-offs?

To answer these types of questions, focused research is being conducted at Sandia National Laboratories in the areas of computers and computing, optimization algorithms, nondeterministic analysis, scientific visualization, numerical simulation of highly nonlinear behavior of large, complex systems in severe thermal and mechanical environments, and other essential enabling technologies. This paper reports on the specific application of some of these tools to characterize the thermal robustness of a concept firing set in a worst-case thermal environment. A 3-D finite-element transient thermal model has been coupled with a nonlinear programming optimization algorithm to solve the inverse problem of determining the worst-case heating configuration in a fire. Then, under conditions of worst-case heating,

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Latin Hypercube Monte Carlo sampling has been used to estimate the expected distribution of the firing set's safety index given uncertainties in the failure criteria of two safety-critical components in the device. The probability of failure of the device is then estimated.

Firing Set Computational Model

This section briefly describes the computational model used for simulations of firing set thermal response. A more detailed description of the model and the computational nature of the highly nonlinear radiative/conductive heat transfer problem is presented in Reference 1. The firing set geometry assumed for this illustrative study is shown in Figure 1, which is an exploded view of the discretized 3-D thermal model. (An assembled unit is shown in Figure 2.) Only half of the firing set need be modeled due to a plane of symmetry in the problem as later described. Over 1800 conduction finite elements exist in the model, with a system of 7 enclosures (1046 radiation surfaces total) used to account for diffuse-gray radiant exchange within the firing set (emissivity = 0.65, representative of fire-oxidized stainless steel).

The candidate firing set housing is a cylindrical thin-walled stainless steel can with a diameter of roughly 6 inches and a height of about 2.6 inches. The representative stainless steel single stronglink assembly (SSA) mates to a hole in the roof of the firing set housing via a perimeter weld. The SSA plate, to which several devices are attached, fits inside a cavity in the SSA. The corners of the plate are bolted to shoulders inside the cavity of the SSA housing. Perfect

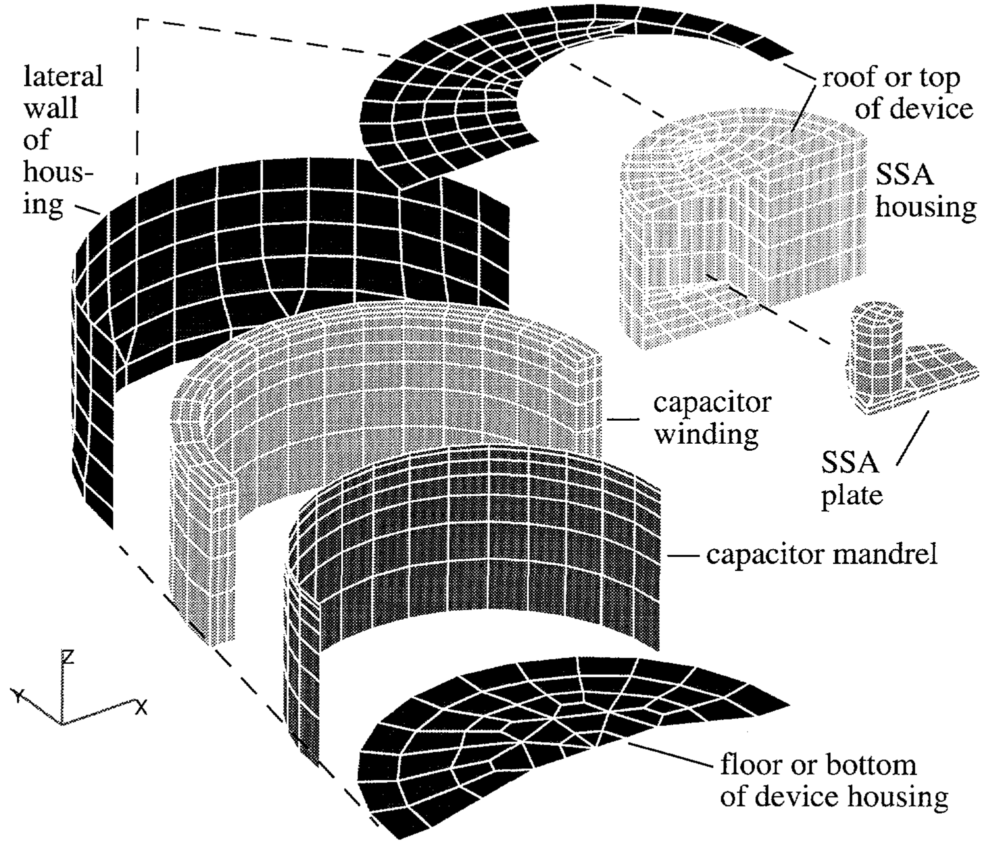

Figure 1 Firing set discretized model geometry (exploded view)

thermal conductance is assumed across all intimate (bolted, welded, mounted, wound) interfaces in the model. The concept capacitor consists of a Mylar-and-foil laminate wound around the stainless-steel mandrel. This type of capacitor winding has highly anisotropic properties because of its layered structure. Thus, the finite elements making up the winding are assigned individually-oriented orthotropic property tensors. The top end of the mandrel, which extends just slightly beyond the winding, is welded to the roof of the firing set housing.

External forcing conditions (heating from the fire source and other boundary conditions) are explained below. The initial temperature in the simulations is always 25° C and the fire temperature is ramped from 25° C to 1000° C over the first 10 seconds of the simulation (and held constant thereafter).

Because of the high temperatures involved, thermal radiation is extremely important in the problem. Radiative transport is a very nonlinear and computationally demanding problem to solve. Additionally, the highly temperature-dependent properties of stainless steel and the large temperature excursions involved contribute to the nonlinearity in the coupled conduction/radiation problem.

Finding the Worst-Case Heating Configuration by Optimization

Here a synopsis is presented of the optimization process required to solve the inverse problem of finding the worst-case exposure of the firing set to a fire. Full technical detail is provided in References 1 and 2.

Firing Set Operation and Relation to Objective Function

The SSA (a.k.a. "stronglink") prevents the transfer of uncleared electrical signals to critical components in the weapon system. It is intended to prevent operation or triggering of a weapon by unauthorized personnel or unintended occurrences. In any operational or abnormal environment it must therefore serve its function until other components in the system necessary for detonation are irreversibly neutralized. In particular, the capacitor winding, which will also be referred to as the "weaklink", must become incapable of holding an electrical charge before the stronglink succumbs.

From a thermal perspective, failure criteria for the weak and strong links is defined in terms of "failure temperatures" that can in general be complex functions of temperature history, heating rate, geometry, boundary conditions, etc. Under thermal conditions in the neighborhood of worst-case heating, the status of the stronglink is deemed indeterminate when certain representative critical elements on the underside (bottom face in Figure 1) of the SSA plate reach 1100° F (~600° C). For the weaklink capacitor, it has been determined that Mylar melts at about 480° F (~250° C), and begins to shrink at significantly lower temperatures. This will eventually lead to a breakdown in its function as a dielectric between the oppositely charged aluminum foils in the winding, allowing the capacitor to short and become irreversibly inoperable. Thus, the present purposes, the failure criterion for the weaklink is taken to be the attainment of a temperature of 480° F anywhere on the capacitor winding.

The objective function for the optimization problem can now be formulated: $t\_fail_{stronglink}$ is defined as the elapsed time (from time zero at the beginning of a given thermal simulation) required for the hottest node anywhere on the underside of the SSA plate to reach a failure temperature of 1100° F; $t\_fail_{weaklink}$ is the time required for the hottest node anywhere on the capacitor winding to reach a failure temperature of 480° F; the difference $t\_fail_{stronglink}$ - $t\_fail_{weaklink}$ is the 'safety margin', and constitutes the objective function to be minimized in the optimization problem by varying the heating configuration. If the worst-case environment can be identified, then the probability of such an event occurring can be estimated, and the device can be hardened to survive it if need be.

Two-Parameter Heating Function

To make the answering of the above question manageable, a simplification is invoked as to the types of heating configurations that the firing set can be exposed to. Only those environments that heat the stronglink preferentially relative to the weaklink are of concern. (Indeed, the degree to which the stronglink is preferentially heated is to be maximized by optimization.) It is apparent that intense heating applied to the roof of the firing set, localized to a region directly above the SSA plate, heats the stronglink preferentially. It is certainly plausible that an accident occurs in which a hydrocarbon fuel fire erupts and melts a hole in the environmental case of a missile, through which a circular region on the top of the firing set is irradiated by the fire, the rest of the firing set being essentially shaded from the it. For simplicity and to maximize the localization of heating in the problem, the limiting case is assumed where the device is completely insulated everywhere except for a circular irradiated region that fully views the fire (view factor to the fire = 1.0). The fire is modeled as a blackbody radiator at a temperature of 1000°C (1832°F). From geometrical and heat transfer considerations it can be concluded that the circular region of heating should be centered on the diametral line corresponding to the plane of symmetry of the device. Thus a plane of symmetry exists in the total thermal problem {geometry + boundary conditions}, and only half of the device need be modeled. This reduces the size of the numerical radiation problem by a factor of about 3 for the given geometry and discretization.

Hence, a two-parameter description of allowable heating configurations is arrived at: radius r of the circular irradiated region is one parameter and location x of the center of this "spot" along the symmetry plane is the other. Figures 2 and 3 show results of a simulation run with the thermal simulation model for a sample parameter set $r = 1.020$ inches and $x = 0.142$ inches = distance from the center of the firing set in the positive x direction as shown in Figure 2. These values define a region on the roof of the device pointed at by the white arrows in Figure 2. High temperatures are concentrated about the stronglink plate, but the capacitor winding is relatively cool. Thus, this combination of parameters results in a highly localized heating configuration that preferentially heats the stronglink to a high degree. Figure 3 shows the relevant weaklink and stronglink temperature responses over time. For the stated parameters the value of the safety margin is ~ 56 minutes.

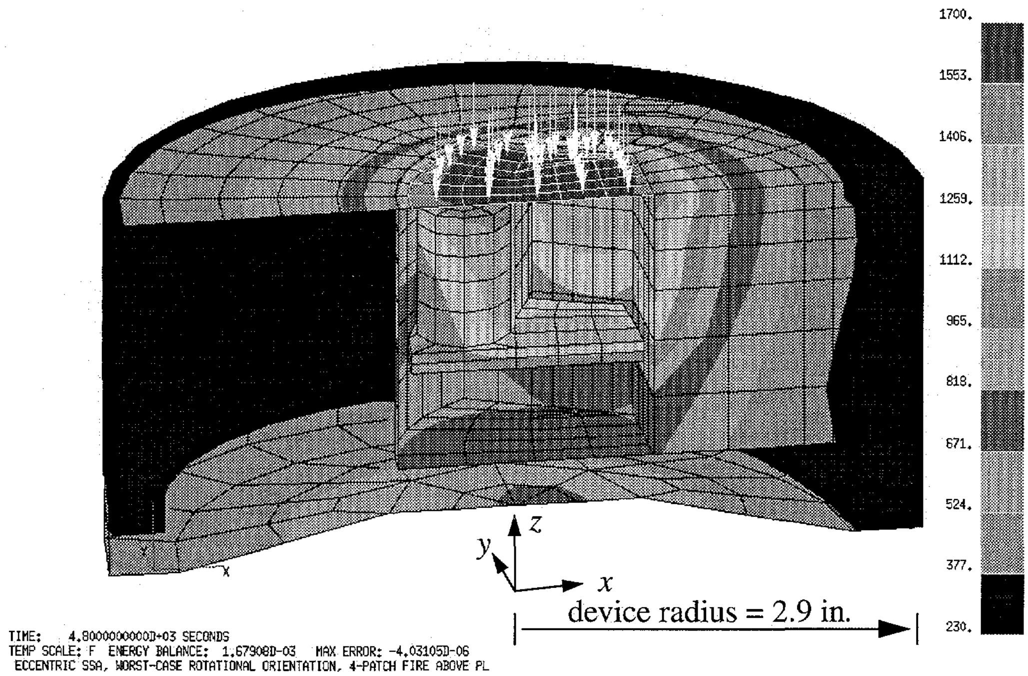

Figure 2 Firing Set temperature distribution (° F) 80 minutes after the start of the fire, heating parameters *r*=1.02 in., *x*=0.142 in.

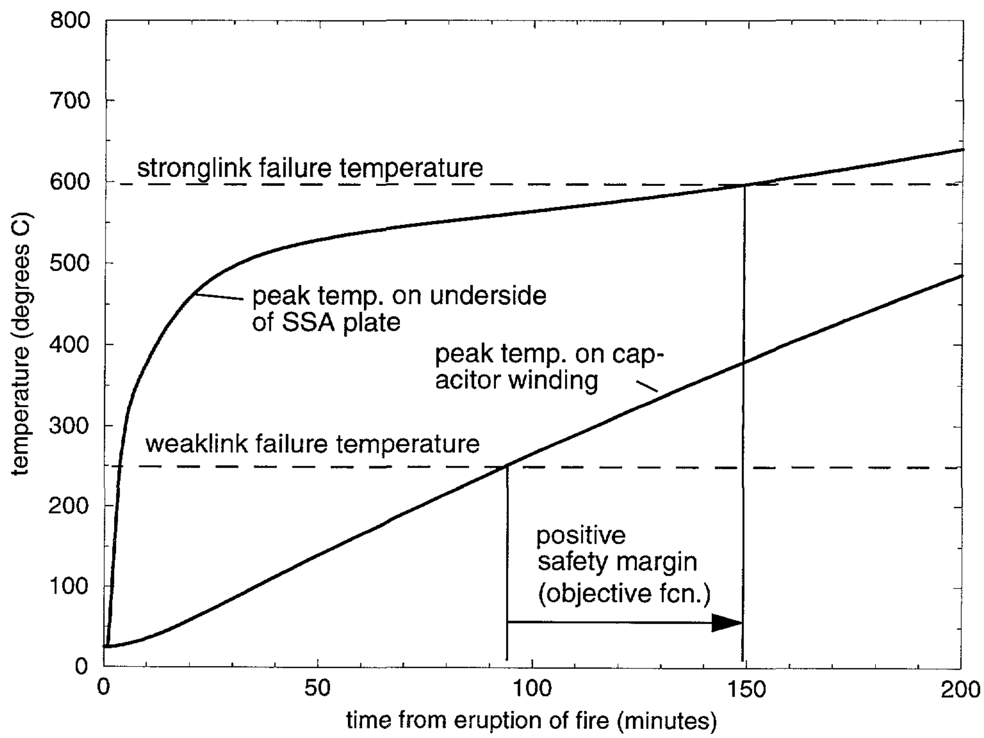

Figure 3 Stronglink and Weaklink temperature histories for *r*=1.02 in., *x*=0.142 in.

Worst-Case Heating Parameters

For a given set of heating parameters {*r*,*x*} a thermal simulation is run and the temperatures of all nodes on the underside of the SSA plate and all nodes of the winding are scanned. Gradient-based nonlinear programming methods (see Ref. 2) are used to select successive parameter sets {*r*,*x*} that successively minimize the safety margin, leading to increasingly threatening heating configurations until the worst-case configuration is found at the minimum safety margin. In this way the inverse problem for determining the worst-case heating configuration is solved.

Figure 4 shows the peak temperatures on the weak and strong links as a function of time for the worst-case heating parameters $r = 1.6204$ inches and $x = 0.78205$ inches determined in the optimization study in Reference 1. The safety margin in this case is only ~ 2.5 minutes. Previous ad hoc searching techniques revealed a much higher worst-case margin of about 20 minutes. *Thus, the use of a systematic procedure, i.e. formal optimization, has resulted in identification of a system vulnerability about one order of magnitude worst than traditional ad hoc searching procedures revealed.* The importance of using systematic procedures is clearly evident.

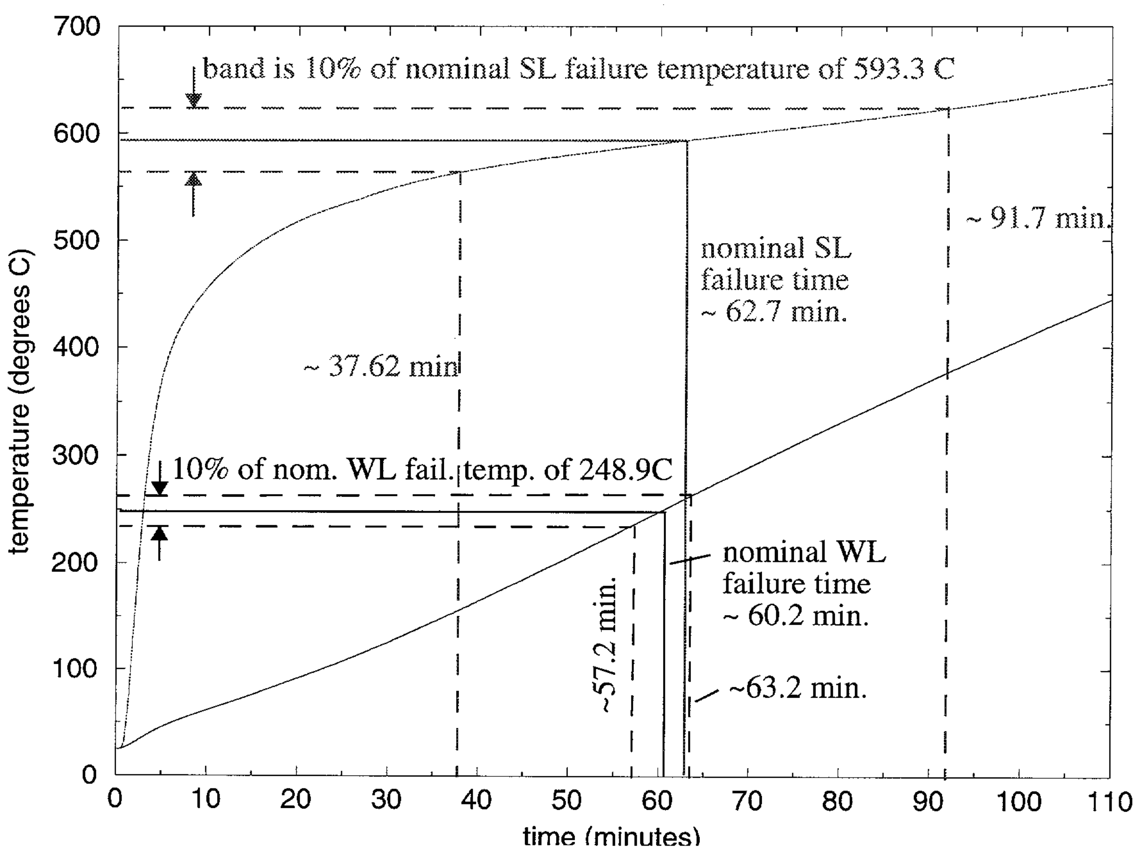

Figure 4 Illustration of effect on safety margin of uncertain for stronglink (SL) and weaklink (WL) failure criteria under worst-case heating scenario x=0.782, r=1.62.

Sensitivity Analysis

Given the temperature responses in Figure 4 and the nominal criteria for stronglink and weaklink failure previously stated ($T\_fail_{stronglink}$ = 1100° F = ~593° C and $T\_fail_{weaklink}$ = 480° F = ~249° C), a safety margin of 2.53 minutes results under worst-case heating circumstances. However, a glance at Figure 4 indicates that stronglink and weaklink failures occur in relatively flat regions of the temperature response curves. This is more true for the stonglink than for the weaklink, but regardless, it can be seen that *the safety margin is very sensitive to the failure temperature criteria. Thus, uncertainty in the failure criteria of the links will have a major impact on the uncertainty of the safety margin.* Indeed, when uncertainty bands 5% above and below the nominal failure temperatures are drawn in the figure, the corresponding bands in failure times indicate that the safety margin could vary anywhere from about 34.5 minutes at best to about -25.5 minutes at worst. Hence, a detailed study of the effects of uncertainty on the safety margin is warranted. The results of such a study are presented next.

Failure Probability by Nondeterministic Analysis

Uncertainty Distributions of the Failure Criteria

The uncertainties in the stronglink and weaklink failure temperatures are assumed to be described by normal distributions with means (μ) equal to the respective nominal failure values of 593° C and 249° C, and standard deviations (σ) equal to 5% of the nominal values, e.g. 29.7° C and 12.4° C, respectively. These would seem to be reasonable variations, certainly not out of the question. For computational purposes, the ranges of the failure-temperature distributions are made finite by truncating them (in this work) at 4σ above and below the mean values.

Sampling Procedure and Results

The Latin Hypercube Sampling (LHS) Monte Carlo code (see Ref. 3) was used to generate, from the above-described uncertainty distributions, N two-parameter sets, each set containing a weaklink and a stronglink failure temperature. The safety margin associated with each parameter set was then obtained by examining the temperature responses in Figure 4 for associated failure times, and then subtracting stronglink failure time from weaklink failure time. The mean and standard deviation of the resulting ensemble of N safety margins were then computed in the standard manner (though this may bias these values as explained in Reference 4, but verification of these results with simple random sampling showed them to be effectively unbiased).

Figure 5 shows the logarithmic convergence behavior for the means and standard deviations of the safety margin ensembles for different numbers of samples. After about 70 samples the estimate of the mean stabilizes to a ~4.26 minute safety margin and the estimate of the standard deviation stabilizes to ~24.8 minutes.

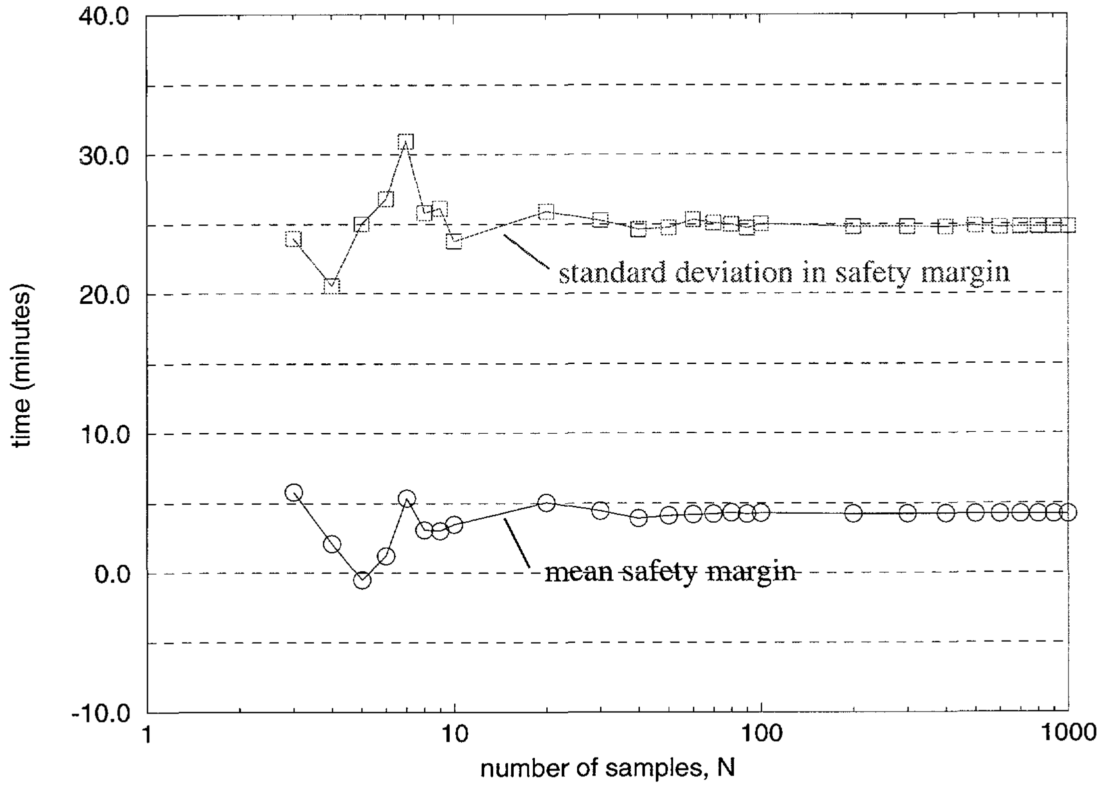

Figure 5 Logarithmic convergence behavior for the means and standard deviations of the resulting safety margin as the population size increases.

Estimation of Failure Probability

The following statistics are based upon a LHS population size of *N*=500, so the statistics are essentially fully stabilized. The estimate of the mean value of the safety margin is found to be 4.28 minutes when uncertainties in the component failure temperatures are accounted for. This value is about 70% greater than the deterministic point estimate of 2.53 minutes at the mean values of the parameters. Thus, *a very significant shift in the expected value of the safety margin occurs in this nonlinear problem with only 5% standard deviations in the normally distributed uncertain failure criteria.* The shift toward a larger expected safety margin is certainly comforting and desirable, *but the very large variance underlying this result yields cause for concern.* Figure 6 shows a histogram in which the safety margin values are binned. The range of the histogram is set by the extreme highest and lowest safety margins attained. The range is divided into 10 equal increments. An examination of the data reveals that *47% of the trials actually result in a* negative *safety margin,* reflecting the very broad 24.85 minute standard deviation in the safety margin population. Furthermore, the bin containing the most results (i.e. the greatest frequency of responses) is in the negative safety margin region. This would clearly be cause for concern if this firing set were in the stockpile and the probability of the thermal scenario posed was high enough. The real message here is that, even though the nominal result might look good, *uncertainties in the problem can be large enough to completely change the outlook of the problem, and nondeterministic analysis is required to get the fuller picture, especially when dealing with issues of high consequence.*

To ascertain the sensitivity of safety margin uncertainty to the **degree** of uncertainty in the input failure criteria, a second study was undertaken in which the standard deviations of the input distributions were halved to 2.5% of the mean (nominal) failure temperatures. The resulting expected value of the safety margin is 2.97 minutes, an increase of 17% from the nominal deterministic result of 2.53 minutes. Comparing this with the 70% shift obtained with input standard deviations twice as large, the shifting of the expected value away from the deterministic value appears to accelerate as the uncertainty in the inputs increases. Figure 7 shows the histogram of the safety margin distribution for 2.5% standard deviations of the inputs. Though the standard deviation of the response drops to 14.1 minutes from the previous case of 24.9 minutes, about 42.6% of the 500 cases analysed still result in a negative safety margin. This has ominous implications as to the viability (robustness) of this particular firing set design under the stated worst-case fire environment because it is vulnerable even with optimistic estimates of the uncertainty of the failure criteria. Thus, *nondeterministic analysis can also affect design decisions by quantifying the robustness or sensitivity of a device's functional behavior to uncertain operating conditions or inputs.*

Summary and Recommendations

An illustration of the coordinated use of computer modeling, optimization, and nondeterministic analysis to assess the thermal robustness of a candidate firing set has been presented. A 3-D nonlinear finite-element heat transfer model of the safing device has been used in conjunction with an optimization algorithm to systematically search out and identify the heating configuration to which the device is most susceptible. The vulnerability of the device has been found to be much greater than traditional ad hoc searching techniques revealed, though the deterministic safety margin under worst-case heating is still positive. Nondeterministic analysis has been applied to estimate the probability of failure at the worst-case point. Reasonable, nonexaggerated uncertainties in the failure criteria of the safety-critical components in the device have been shown with Monte Carlo sampling to result in >40% probabilities of failure. Thus, the relative safety level of the firing set design is much lower than less sophisticated computer techniques initially suggested. This study is the initial step in research aimed at developing nondeterministic optimization procedures where optimization and nondeterministic analysis are combined to find the worst-case heating point as defined by greatest probability of failure. It is recommended that such techniques be routinely applied in weapon design and assessment to produce more fully characterized and robust systems where weapon surety is paramount. These methods can also be used in design and resource allocation processes to build safer, more reliable, more optimal systems.

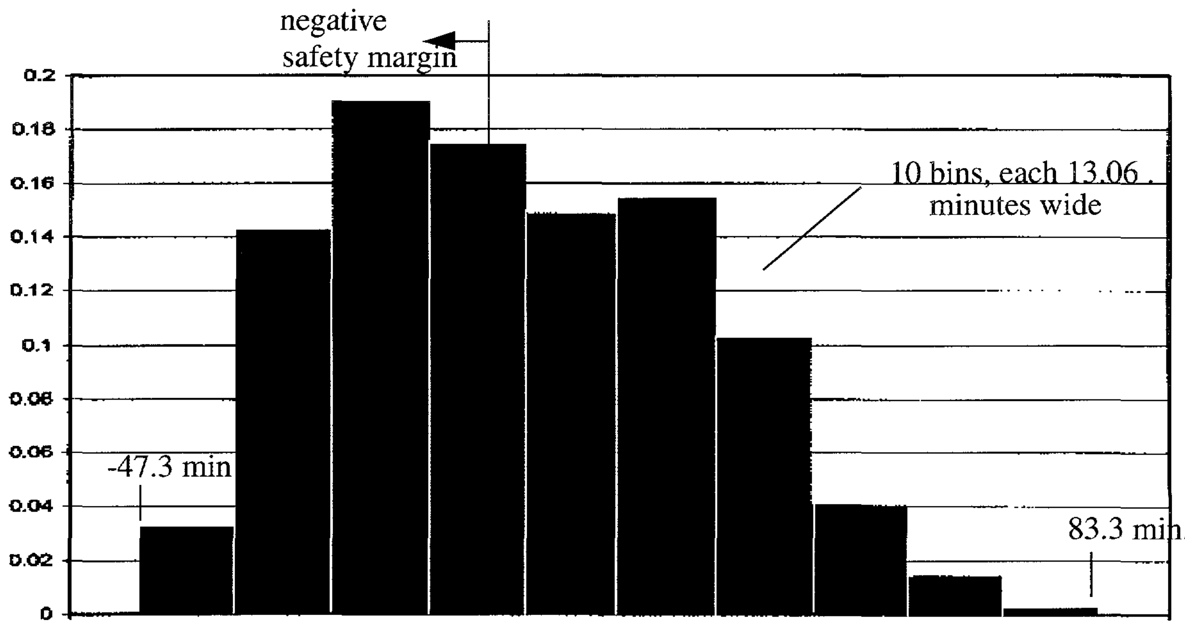

Figure 6 Histogram of safety margins generated from 500 LHS sets, baseline standard deviations of inputs are 5% of nominal (mean) values.

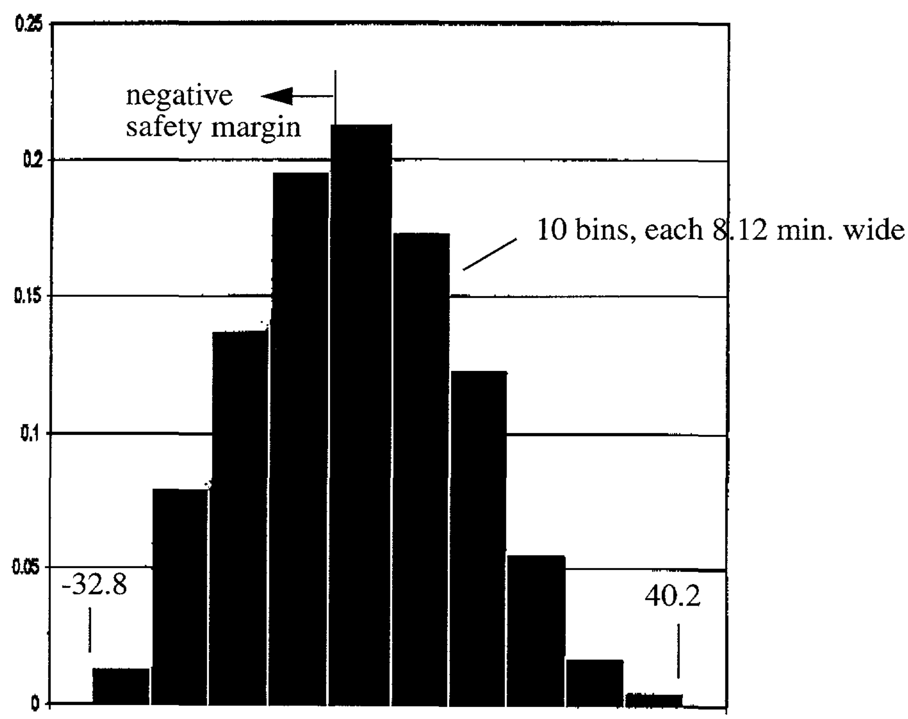

Figure 7 Histogram of safety margins generated from 500 LHS sets, reduced standard deviations of inputs are 2.5% of nominal

References

1. Romero, V.J., Eldred, M.S., Bohnhoff, W.J., and Outka, D.E., "Application of Optimization to the Inverse Problem of Finding the Worst-Case Heating Configuration in a Fire," Numerical Methods in Thermal Problems, Vol. IX, Part 2, pp. 1022-1033, Pineridge Press, R.W. Lewis and P. Durbetaki, ed., proceedings of the 9th Int'nl. Conf. on Numerical Methods in Thermal Problems, Atlanta, GA, U.S.A., July 17-21, 1995.

2. Eldred, M.S., Outka, D.E., Fulcher, C.W., and Bohnhoff, W.J., "Optimization of complex mechanics simulations with object-oriented software design," proceedings of the 36th AIAA Structures, Structural Dynamics, and Materials Conf., April 10-13 1995, New Orleans, LA., part IV, pp. 2406-2415.

3. Iman, R.L., and Shortencarier, M.J., "A FORTRAN77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples to Use with Computer Models," Sandia National Laboratories report SAND83-2365 (RG), printed March 1984.

4. McKay, M.D., Conover, W.J., and Beckman, R.J., "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code," Technometrics, 21, 239-245.

Biography

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Vicente Romero has been with the Thermal Sciences Department at Sandia for 9 1/2 years. His primary interest and expertise is in numerical and computational methods for modeling nonlinear physical phenomena, often with a statistical or stochastic element of behavior. He has developed numerical algorithms and software for modeling the concentration of solar irradiation under stochastic reflector surface conditions, Monte Carlo modeling of laser light propagation and induced fluorescence in participating media, free-surface fluid flows, and radiative, conductive, and convective heat transfer in various thermal systems. Vicente also has extensive experience as a thermal analyst modeling weapon systems in fire environments. His most recent involvement in this area consists of research, development, and application of weapon safety assessment methods utilizing optimization and nondeterministic techniques coupled with large simulation models.

Vicente received his PhD in Mechanical Engineering in 1996 at the University of New Mexico., an M.S.M.E. degree from Stanford University in 1988, and a B.S.M.E. from New Mexico State University in 1986.